Validating AIRS upper atmosphere water vapor retrievals using aircraft and balloon in situ measurements

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[1] This paper provides an initial assessment of the accuracy of the Atmospheric Infrared Sounder (AIRS) water vapor retrievals from 500 to 100 mbar. AIRS satellite measurements are compared with accurate aircraft (NASA WB57) and balloon in situ water vapor measurements obtained during the NASA Pre-Aura Validation Experiment (Pre-AVE) in Costa Rica during Jan. 2004. AIRS retrieval (each pressure level of a single footprint) of water vapor amount agrees with the in situ measurements to ~25% or better if matched closely in time (1 hr) and space (50–100 km). Both AIRS and in situ measurements observe similar significant variation in moisture amount over a two-day period, associated with large-scale changes in weather patterns. *INDEX TERMS:* 0365 Atmospheric Composition and Structure: Troposphere—composition and chemistry; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; 3394 Meteorology and Atmospheric Dynamics: Instruments and techniques. **Citation:** Hagan, D. E., C. R. Webster, C. B. Farmer, R. D. May, R. L. Herman, E. M. Weinstock, L. E. Christensen, L. R. Lait, and P. A. Newman (2004), Validating AIRS upper atmosphere water vapor retrievals using aircraft and balloon in situ measurements, *Geophys. Res. Lett.*, *31*, L21103, doi:10.1029/2004GL020302.

1. Introduction

[2] An accurate knowledge of the distribution of upper atmospheric water vapor is needed for climate change assessment and weather prediction [*Hartmann*, 2002, and references therein]. Since September 2002 this important greenhouse gas has been measured by the Atmospheric Infrared Sounder (AIRS) onboard the Earth Observing System *Aqua* satellite platform. Twice daily over most of the globe, AIRS provides moisture and temperature soundings of the atmosphere at 12 standard pressure levels over a spatial footprint of 45 km. The value of AIRS water vapor measurements for weather and climate studies critically depends on establishing accuracy limits for these derived quantities. The pre-launch requirement for retrieval uncertainty in the AIRS water vapor humidity profile was 20%, with a goal of 10% in 2 km layers below 100 mbar [*Aumann et al.*, 2003]. A plan [*Fetzer et al.*, 2003a] to validate the AIRS retrievals was based on comparison with operational radio sondes. However, in the upper troposphere and lower stratosphere (UT/LS), radio sonde measurements are not considered accurate for absolute water vapor abundances [*World Meteorological Organization*, 2000].

[3] Some of the most precise and accurate in situ measurements of water vapor in the UT/LS have been made from instruments that use IR laser absorption spectroscopy and Lyman-alpha flourescence [*Webster et al.*, 1994; *Webster and Heymsfield*, 2003; *May*, 1998; *Hintsa et al.*, 1999; *Weinstock et al.*, 1994]. During the NASA Pre-Aura Validation Experiment (Pre-AVE) that took place during January 2004, four in situ instruments, the Aircraft Laser Infrared Absorption Spectrometer (ALIAS), the Harvard water vapor instrument, the JPL Laser Hygrometer and diode laser balloon hygrometers were flown simultaneously near San José, Costa Rica for comparison with AIRS during coincident overpasses of the *Aqua* satellite. The aircraft (NASA WB-57) and balloon instruments made several flights recording ascent and descent profiles of water vapor, total water and water isotopes. Intercomparisons of satellite and in situ data provide a first opportunity to assess the accuracy of UT/LS water vapor retrievals from AIRS.

2. Description of Instruments

[4] AIRS is a medium resolution infrared grating spectroradiometer. As a multi-aperture slit and pupil-imaging system, a diffraction grating disperses the incoming infrared radiation into 17 linear detector arrays comprising 2378 spectral samples. At long wavelengths, the spectral resolution is about 0.5 cm^{-1} decreasing to about 2 cm^{-1} at shorter wavelengths. The retrieval of the AIRS water vapor profile is based on iterative least squares physical inversion of clear column radiances following the approach of *Chahine* [1968, 1977]. The retrieval of the AIRS water vapor profile uses a large set of channels associated with the strong 6-μm water band [*Susskind et al.*, 2003]. Water vapor amount is retrieved at twelve standard pressure levels between the surface and 100 mbar.

[5] ALIAS is a high resolution four-channel scanning Tunable Diode Laser (TDL) and Quantum-Cascade (QC) laser spectrometer (3.4 to 8 μm) that makes direct, simultaneous measurements of H_2O, HCl, NO_2, CH_4, N_2O, CO, and water isotopes in the stratosphere and troposphere at sub-parts-per-billion sensitivities [*Webster et al.*, 1994]. ALIAS has flown over 300 times in eight major NASA missions. Because the ALIAS inlet vaporizes all liquid water and ice particles, ALIAS provides a measurement of total water (accuracy ~5%).

[6] The JPL Laser Hygrometer (JLH) is a single-channel, multi-pass, near-infrared, open-path tunable diode laser

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Table 1. Dates and Approximate Times (UTC) of Instrument Observations During Profiles[a]

	AIRS	Aircraft Sensors	Sondes
January 27	0700	1630 2042	1730
January 28	1832		1745
January 29	1920	1650 2028	1725

[a]The profiles were obtained near 10 N, 84.15W. On January 28, sonde water vapor data were obtained only above 300 mbar due to damage to the short path optical cell of the diode laser hygrometer during launch.

spectrometer for in situ measurements of atmospheric water vapor [*May*, 1998]. The laser and optics extend beneath a right wing hatch on the WB-57F aircraft out into the free air stream, eliminating sampling issues due to evaporation of condensed water. JLH utilizes harmonic absorption spectroscopy, a common sensitivity-enhancing technique employed in diode laser spectroscopy [*Webster et al.*, 2001], yielding a water detection range of 0.1 to 1000 parts-per-million-by-volume (ppmv) at typically 5 to 10% absolute accuracy.

[7] The Harvard water vapor instrument uses photofragment resonance fluorescence to measure water vapor in the troposphere and lower stratosphere [*Weinstock et al.*, 1994]. Quoted accuracy for the water vapor instrument, as validated by laboratory calibrations, in situ vacuum ultraviolet absorption, and in-flight intercomparisons with the JPL TDL [*May*, 1998] is ±5%. Although the Harvard and JPL instruments agree to within 5%, they do not agree well with other water vapor instruments, also believed to be accurate to 5–10% levels [*World Meteorological Organization*, 2000].

[8] The balloon sonde hygrometer design is similar to an open-path, near-infrared (1.37 μm) TDL instrument developed for aircraft measurements [*May*, 1998]. The hygrometer consists of an open, dual-path optical absorption cell (4.03 m optical path for stratospheric measurements and 13.4 cm path for tropospheric measurements). A fiber-coupled laser is split into two separate beams (80% for the multipass portion of the optical path and 20% for the shorter path). Prototype sondes were successfully tested in September 2003 at the National Upper Atmosphere Balloon Facility in Ft. Sumner, New Mexico. Each laser diode hygrometer is calibrated prior to flight and the expected accuracy is 5%.

[9] The dates and times of Pre-AVE flights used in comparison with AIRS are shown in Table 1. The orbital path of the Aqua satellite placed the AIRS instrument in a coincident crossing of San José on January 29, bracketed within about two hours by the WB57 ascent and return to the city and by a sonde launch. A night overpass of AIRS occurred about 9 hours earlier than the aircraft flight on January 27. On both days the sonde remained in close proximity to San José. An additional sonde was launched on January 28.

3. Profile Comparisons

[10] The aircraft and balloon water vapor measurements in Figures 1a and 2a generally agree to within 10–20% in most regions of the vertical profile and show consistency in the detailed structure as well as significant variation in water vapor with height. The satellite water vapor retrievals (black triangle) are mean layer amounts [*Fishbein*, 2001]. For example, the retrieved value at the standard pressure level of 500 mb is the mean layer mixing ratio from 500 to 400 mb. The profiles of Figures 1b and 2b are the percentage differences of the in situ measurements from the satellite observations. Aircraft and balloon ascent profiles are shown as black symbols, while aircraft descent profiles are shown as colored symbols. The in situ measurements have been averaged to correspond to the AIRS layers. The retrieval uncertainty of the satellite observations is shown as dashed lines.

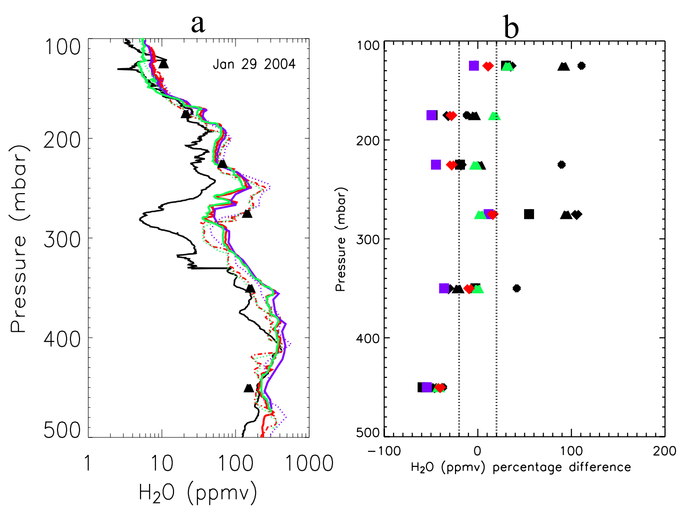

Figure 1. (a) Ascending (solid lines) and descending (dashed lines) profiles for January 29 2004. ALIAS (green) JPL Laser Hygrometer (red), Harvard instrument (purple), laser hygrometer sonde (black line) and AIRS retrieved mean layer mixing ratio (black symbol) corresponding to 500–400 mb layer, 400–300 mb layer, 300–250 mb layer, 250–200 mb layer, 200–150 mb layer and 150–125 mb layer. (b) The percentage difference of the AIRS and in situ measurements. Ascent profiles are shown as black symbols, and measurements for the descent profiles are shown in color. ALIAS (green, triangle), JPL Laser Hygrometer (red, diamond), Harvard water instrument (purple, box), laser hygrometer sonde (black, circle).

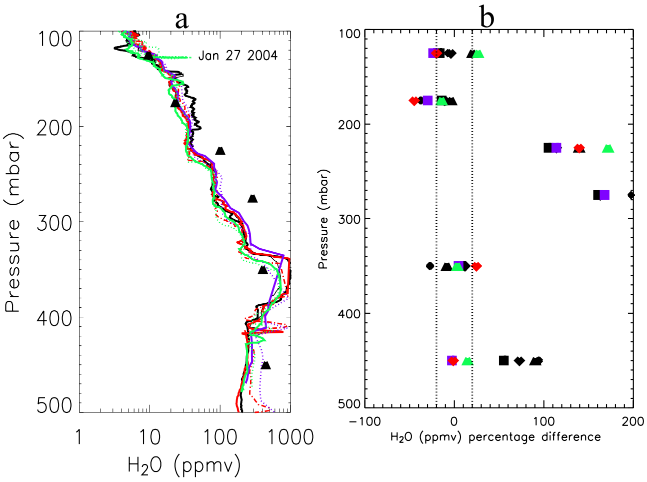

Figure 2. Same as Figure 1 but for January 27 2004.

[11] On January 27, the satellite data were acquired during night several hours prior to the aircraft and balloon flights. The in situ measurements and satellite retrievals are matched within one to two hours on January 29. The agreement between the aircraft in situ and satellite measurements is better on January 29 for the descent profiles. The descent profiles occurred within an hour of the satellite overpass. In most regions of the descent profiles, the percentage differences of the situ and satellite measurements fall within the uncertainty of both the satellite retrievals (20%) and the in situ measurements (5–10%). Both satellite and in situ measurements show drier conditions on January 27 compared to January 29. The balloon and satellite profiles in Figure 3 show the transition to a drier column over a three-day period, especially for regions below 200 mbar. Above 200 mbar, the AIRS measurements do not vary by more than a few percent, whereas both aircraft and laser hygrometer measurements show a decrease in water vapor mixing ratio by 15 to 30%.

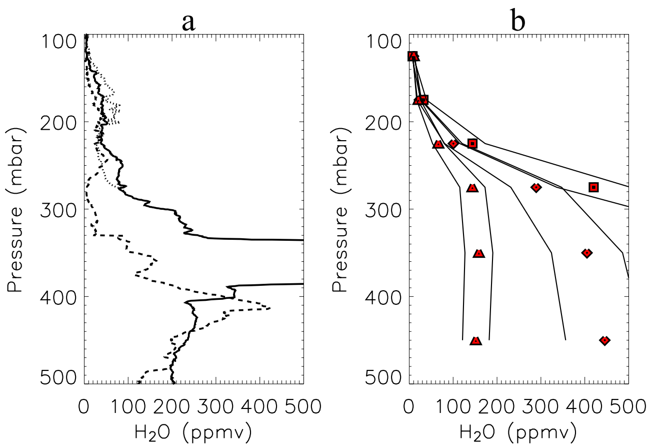

Figure 3. (a) diode laser sonde measurements for January 27 (solid), January 28 (dots) and January 29 (dashed). (b) AIRS water vapor retrievals for January 27 (box), January 28 (diamond) and January 29 (triangle); solid lines show pre-launch retrieval measurement uncertainty of 20%.

[12] The spatial change in moisture distribution over this period is illustrated by Figure 4, which shows AIRS retrievals of water vapor mixing ratio at 300 and 500 mbar for January 27 and January 29. At these levels, the moisture retrieval varies about 10% between AIRS footprints. Water vapor levels in the upper troposphere over Costa Rica are typically determined by either transport of dry air from the Eastern Pacific, or advection of wet air from the Amazon basin as a result of east-west movement of an anti-cyclone

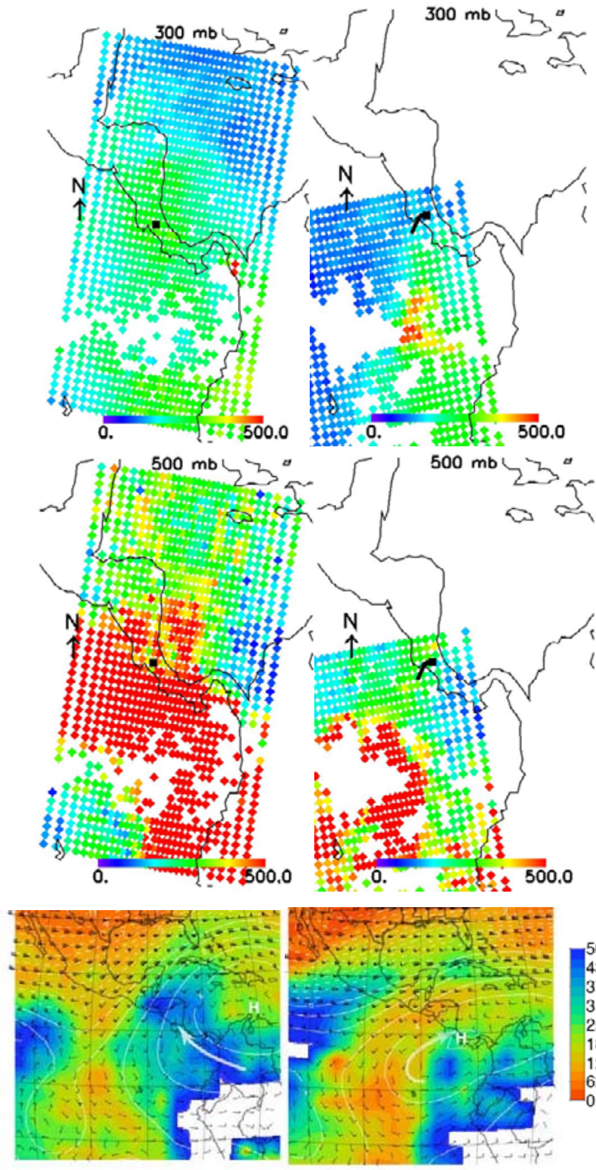

Figure 4. Maps of AIRS water vapor (ppmv) at 300 and 500 mbar and the NCEP MRF analysis at approximately 300 mbar for January 27 (left column) and January 29 (right column). The black box marks the position of San José, and dashed line the flight line of the WB57 leaving San Jose on January 29. The white contours (lower panels) show the non-divergent stream function and the black barbs indicate the winds (in m). Winds blow parallel to the white contours and the wind strength is directly proportional to the spacing of the white contours. The thick semi-transparent line indicates the direction of flow into Costa Rica.

located over the Caribbean region. On January 27, an upper level trough located to the west of Costa Rica pulled moist air from the northern part of South America over Costa Rica. When this trough weakened two days later, the center of the anti-cyclone moved west towards Central America, bringing dry air from the Eastern Pacific over Costa Rica, as shown by the NCEP MRF analysis in Figure 3. The decrease in moisture over the San José area as a result of this upper air movement is evident in the AIRS maps at 300 and 500 mbar.

4. Summary and Discussion

[13] A first validation of AIRS upper atmosphere water vapor retrievals with aircraft and balloon measurements over land has been carried out in the tropics. The comparisons are made between well-resolved vertical in situ profiles at six AIRS standard pressure levels from 500 to 100 mbar. The agreement with aircraft and in situ data for an AIRS retrieval (each pressure level of a single footprint) is 25% or better for measurements closely matched in both time (one hour) and space (<100 km). *Fetzer et al.* [2003b] report a root-mean-square uncertainty greater than 50% in AIRS retrievals between 500 and 350 mbar based on operational radio sondes for the initial version of AIRS products. Our study suggests that spatial sampling differences due to the small scale structure of water vapor likely contributed to this earlier large estimate of uncertainty, especially considering the close proximity of many operational radio sondes to coastal regions.

[14] All in situ sensors measured a decrease in water amount above 200 mb between January 27 to January 29. Significantly, the AIR retrieved values for the 150 mb level do not change from one date to the other, even though during this same time frame AIRS correctly retrieves the variability of water vapor below this level. The capability to retrieve water vapor at these heights may be limited by the lack of independent spectral radiance information available for the retrieval, combined with instrument measurement uncertainty [*Pagano et al.*, 2002]. Although in an absolute sense, these small differences between the in situ and satellite data are not very important in terms of total column moisture amount, the capability to measure small changes is important for quantitative studies of UT/LS transport. The profile comparisons demonstrate that further validation of AIRS UT/LS water vapor retrievals requires a carefully designed combination of observation strategies that would include additional aircraft and balloon instrument measurements very close in time with the satellite overpass. Additional data sets and analyses are needed to fully describe the accuracy and sensitivity of AIRS for measurements of UT/LS water vapor. This study shows, however, that AIRS accurately measured the variability in water vapor below 150 mb associated with a short-term change in upper atmospheric circulation.

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